

# Primordial Nucleosynthesis

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Primordial or big bang nucleosynthesis (BBN) is now a parameter free theory whose predictions are in good overall agreement with observations. However, the  ${}^7\text{Li}$  calculated abundance is significantly higher than the one deduced from spectroscopic observations. Most solutions to this *lithium problem* involve a source of extra neutrons that inevitably leads to an increase of the deuterium abundance. This seems now to be excluded by recent deuterium observations that have drastically reduced the uncertainty on D/H and also calls for improved precision on thermonuclear reaction rates.

**KEYWORDS:** Big bang nucleosynthesis, Lithium, Deuterium, Thermonuclear reaction rates

## 1. Introduction

Primordial nucleosynthesis is one of the three historical strong evidences for the hot big bang model. Its last free parameter, the baryon-to-photon ratio of the Universe, is now deduced from observations of the anisotropies of the cosmic microwave background radiation (CMB), with a precision better than one percent [1]. There is a good agreement between the primordial abundances of  ${}^4\text{He}$  and D, deduced from observations, and from primordial nucleosynthesis calculations. However, the  ${}^7\text{Li}$  calculated abundance is significantly higher than the one deduced from spectroscopic observations. Solutions to this problem that have been considered include stellar surface depletion of lithium, nuclear destruction during BBN or solutions beyond the standard model (see [2] for a review). Experiments have now excluded a conventional nuclear physics solution (see e.g. [3] and references therein), even though a few uncertain reaction rates could marginally affect Li/H predictions. This lithium problem has recently worsened. Most non-conventional solutions lead to an increase of deuterium production. However, recent deuterium observations have drastically reduced the uncertainty on primordial D/H abundance [4], excluding such increase. With a precision of 1.6% on the observed D/H value [4], comparison with BBN predictions requires that the uncertainties on thermonuclear reaction rates governing deuterium destruction be reduced to a similar level.

## 2. Recent results

In our latest work [5], we adopted for the baryon-to-photon ratio, the constraints obtained with the largest set of CMB data (TT,TE,EE+lowP), without any external data, giving  $\Omega_b h^2 = 0.02225 \pm 0.00016$ , together with  $N_\nu=3$  for the number of neutrino families and  $\tau_n = 880.3 \pm 1.1$  s [6] for the neutron lifetime. The nuclear reaction rates are those listed in [7] with only a few updates listed below. Recently, Hou *et al.* [14] have re-evaluated the  ${}^7\text{Be}(n,\alpha){}^4\text{He}$  cross section, based on  ${}^4\text{He}(\alpha,n){}^7\text{Be}$ ,  ${}^4\text{He}(\alpha,p){}^7\text{Li}$  and  ${}^7\text{Li}(p,\alpha){}^4\text{He}$  experimental data, using charge symmetry and/or detailed balance principles. An improved evaluation of the  ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$  reaction rate has been published [8], using a Monte-Carlo based R-matrix analysis. The effect of these re-evaluations can be seen between columns 2 and 3 in Table I, while columns 4 shows the effect of the re-evaluated reaction rates [5]

for deuterium destruction (see § 3). Column 5 represent the results of a Monte Carlo calculation [5] as described in [7, 9] but with these few new rates, to be compared with observations in Column 6.

**Table I.** Primordial abundances compared to observations.

	a	b	c	d	Observations	Cyburt et al. [10]
$Y_p$	0.2482	0.2482	0.2484	$0.2484 \pm 0.0002$	$0.2449 \pm 0.0040$ [11]	$0.24709 \pm 0.00025$
D/H ( $\times 10^{-5}$ )	2.635	2.635	2.452	$2.45 \pm 0.05$	$2.53 \pm 0.04$ [4]	$2.58 \pm 0.13$
$^3\text{He}/\text{H}$ ( $\times 10^{-5}$ )	1.047	1.047	1.070	$1.07 \pm 0.03$	$1.1 \pm 0.2$ [12]	$1.0039 \pm 0.0090$
$^7\text{Li}/\text{H}$ ( $\times 10^{-10}$ )	5.040	5.131	5.651	$5.61 \pm 0.26$	$1.58^{+0.35}_{-0.28}$ [13]	$4.68 \pm 0.67$

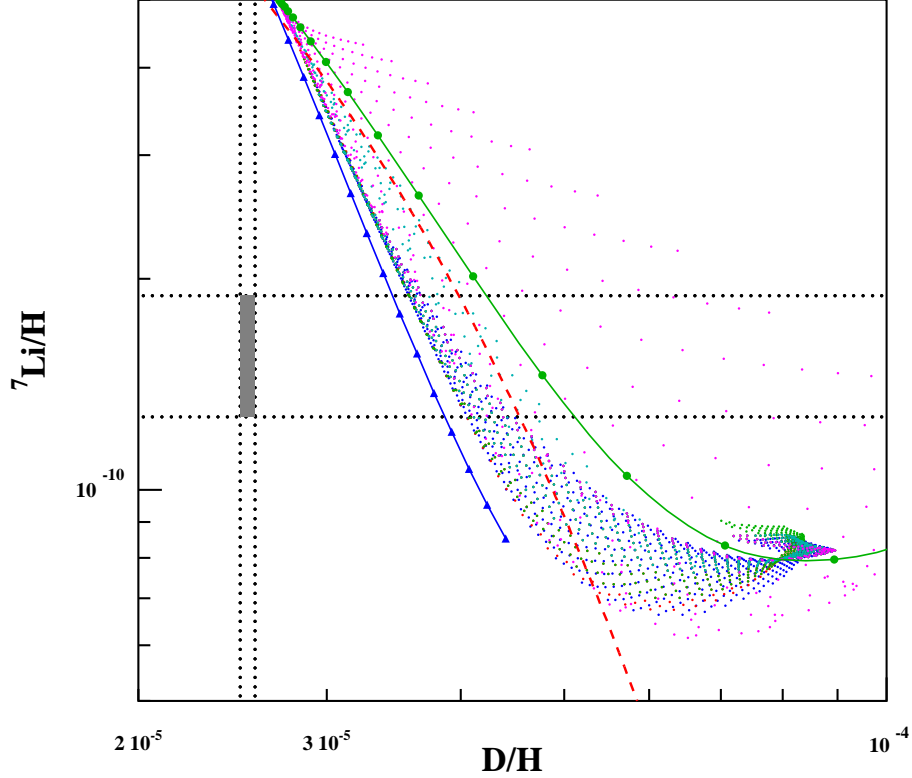
Baseline (a), update of  $^7\text{Be}(n,\alpha)^4\text{He}$  [14] and  $^3\text{He}(\alpha,\gamma)^7\text{Be}$  [8] rates (b), together with D(d,n) $^3\text{He}$ , D(d,p) $^3\text{H}$  and D(p, $\gamma$ ) $^3\text{He}$  new rates [5] (c), Monte Carlo ( $1\sigma$ ) (d) from Coc *et al.* [5].

It is apparent in Table I that the lithium prediction is higher than observations by a factor  $\approx 3.5$ , but also that deuterium predictions are only marginally compatible with recent observations [4]. The last column in Table I displays the results of a very recent review by Cyburt et al. [10] showing only small differences with our work. They virtually disappear when the new rates discussed above are adopted in both calculations (Tsung-Han Yeh, *priv. comm.*), except for  $^4\text{He}$ , due, apparently, to different corrections to the weak rates.

### 3. $^7\text{Li}$ and D nucleosynthesis

For the CMB deduced baryon-to-photon ratio,  $^7\text{Li}$  is produced indirectly by  $^3\text{He}(\alpha,\gamma)^7\text{Be}$ , where  $^7\text{Be}$  will much later decay to  $^7\text{Li}$ , while  $^7\text{Be}$  is destroyed by  $^7\text{Be}(n,p)^7\text{Li}(p,\alpha)^4\text{He}$ . The solutions to the lithium problem generally rely on an increased late time neutron abundance to boost  $^7\text{Be}$  destruction through the  $^7\text{Be}(n,p)^7\text{Li}(p,\alpha)^4\text{He}$  channel. Figure 1 summarizes the results on  $^7\text{Li}$  and D predictions by different models than include late time neutron injection aiming at reducing the  $^7\text{Be}+^7\text{Li}$  production, but at the expense of D overproduction. These models involve mirror neutrons, dark matter decay or annihilation [15] or coupled variation of constants (affecting the  $^1\text{H}(n,\gamma)^2\text{H}$  rate) [16] as extra neutron sources. These extra neutrons, inevitably, also boost the D and  $^3\text{H}$  production through the  $^1\text{H}(n,\gamma)^2\text{H}$  and  $^3\text{He}(n,p)^3\text{H}$  channels, respectively [17]. The dashed curve [5] represent an approximation [Eq. 7.4 in [5]] of the interplay between Li/H and D/H when neutrons are injected towards the end of BBN ( $T < 0.5$  GK). In this approximation, the flow through the  $^3\text{He}(n,p)^3\text{H}$  reaction is neglected but it shows up in the lower limit ( $\approx 0.6 \times 10^{-10}$  in Fig. 1) reached in Li/H:  $^7\text{Li}$  is produced by the  $^3\text{He}(n,p)^3\text{H}(\alpha,\gamma)^7\text{Li}$  reaction at low temperature when the  $^7\text{Li}(p,\alpha)^4\text{He}$  reaction is less efficient. The figure shows that many models [17, 18] are able to bring the lithium abundance within the observational limits but at the expense of an increased D/H abundance ( $\approx 4 \times 10^{-5}$ ), now excluded by observations. In addition, it was noted by Kusakabe et al. [17] that the ratio of  $^1\text{H}+n$  to  $^7\text{Be}+n$  cross sections increases with energy, rendering less efficient the injection of non-thermalized neutrons (from heavy relic decays e.g. [18]) for destroying  $^7\text{Be}$  without overproducing deuterium.

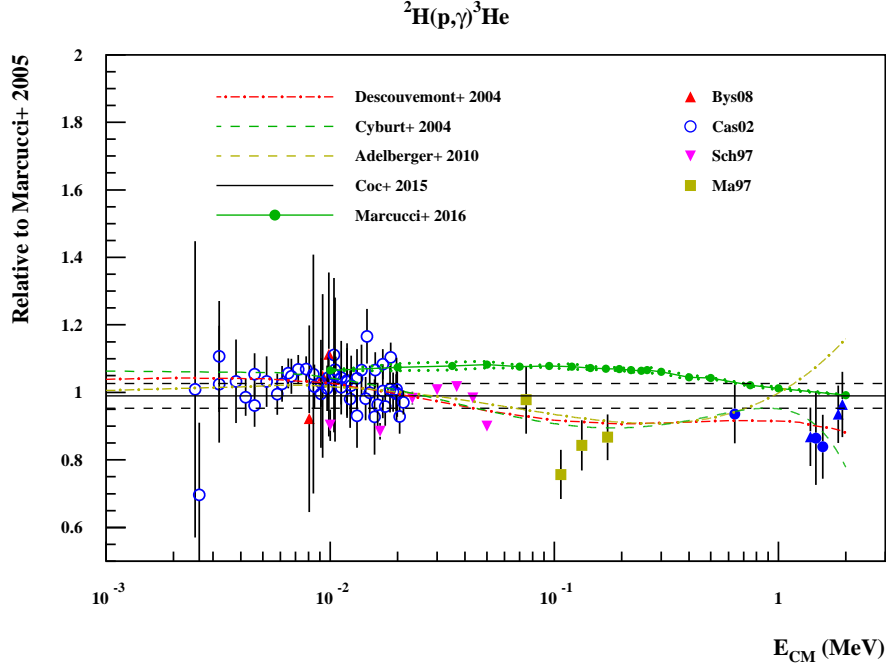
Leaving aside this unsolved lithium mystery, the precision of 1.6% (or better [19]) on the observed D/H value [4], requires that the uncertainties on the D(p, $\gamma$ ) $^3\text{He}$ , D(d,n) $^3\text{He}$  and D(d,p) $^3\text{H}$  rates that govern deuterium BBN destruction be reduced to a similar level. Indeed, a +1% variation of these rates induces a respectively -0.32, -0.46 and -0.54% variation of D/H [5]. Achieving such a precision on nuclear cross sections is a very difficult task: data from different experiments need to be combined keeping in mind the importance of systematic uncertainties, in particular concerning the absolute normalization. Two main philosophies are found in evaluations of reaction rates: *i*) follow closely experimental  $S$ -factor experimental data or *ii*) use theoretical input for the shape of the  $S$ -factor. We



**Fig. 1.** Lithium–deuterium anti–correlation in BBN induced by different models involving neutron injection (dots: update of Fig. 9 in Ref. [15], green circles: Fig. 7 in Ref. [15] and blue triangles, Fig. 12 in Ref. [16]). The horizontal and vertical dotted lines rerepresents the observational Li/H [13] and D/H [4] constraints while the dashed line is a qualitative explanation of the anti–correlation.

chose the second option, with Marcucci *et al.* [20]  $[D(p,\gamma)^3\text{He}]$  and Arai *et al.* [21]  $[D(d,n)^3\text{He}]$  and  $[D(d,p)^3\text{H}]$  as theoretical  $S$ –factors, keeping the normalization ( $\alpha$ ) as a free parameter that has to be determined by comparison with experimental data. The procedure we followed [5] for the  $D(p,\gamma)^3\text{He}$  reaction was *i)* to select experimental datasets [22–25] for which systematic uncertainties were provided, *ii)* determine for each data set, by  $\chi^2$  minimization, the normalization factor to be applied to the theoretical  $S$ –factor of Marcucci *et al.* [20], *iii)* add quadratically the systematic uncertainties and *iv)* perform a weighted average of the normalization factor. We obtained  $\alpha = 0.9900 \pm 0.0368$  for this factor, that was subsequently used to scale the Marcucci *et al.*  $S$ –factor, and calculate the thermonuclear  $D(p,\gamma)^3\text{He}$  reaction rate and associated uncertainty. This result is quite robust given the data and the theoretical  $S$ –factor, as verified using bayesian techniques instead [26]. Comparison between experimental data, fits and theories is displayed in Fig. 2 (normalized to the Marcucci *et al.* (2005) theoretical  $S$ –factor). It shows that previous fits [27–29] were driven down by the scarce data at BBN energies. This is not the case anymore when the theoretical energy dependence of Marcucci *et al.* (2005) is assumed. However, an improved calculation of the  $S$ –factor by Marcucci *et al.* (2016) [30] lies significantly above the previous calculation: if one applies the same renormalisation method one finds  $\alpha = 0.915 \pm 0.038$ . We used the same procedure for  $D(d,n)^3\text{He}$  and  $D(p,\gamma)^3\text{He}$  except that

the theoretical  $S$ -factor is taken from Arai *et al.* [21]. All three reaction rates are higher than previous evaluations at BBN temperatures leading to a decrease in the D/H prediction, as shown in Table I. In addition, if we now use the theoretical  $S$ -factor from Marcucci *et al.* (2016), we obtain an additional reduction of  $\Delta(\text{D}/\text{H}) = -0.072 \times 10^{-5}$  that vanished if we rescale it ( $\alpha=0.915$ ) to fit experimental data.



**Fig. 2.** Ratio of experimental [22–25], fitted [5, 27–29] and new theoretical [30]  $S$ -factors to the theoretical one [20]; the horizontal lines correspond to the theoretical  $S$ -factor scaled by  $\alpha \pm \Delta\alpha$  [5]. (Systematic uncertainties in the range 4.5–9% are not shown.)

#### 4. Summary and conclusions

As conclusions, we list below our comments regarding frequently asked questions concerning big bang nucleosynthesis.

- *There is no nuclear solution to the lithium problem.* Extensive sensitivity studies [7] have not identified reactions, beyond those already known, that could have a strong impact on lithium nucleosynthesis. Unknown resonances that could sufficiently increase the cross sections of reactions that destroy  ${}^7\text{Be}$  were not found experimentally (see e.g. [3] and references therein) and in any case would have too low strengths [31] because of the Coulomb barrier.
- However, *without solving the lithium problem*, uncertainties affecting a few reaction rates, like  ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ , may still affect the lithium production. The role of the  ${}^7\text{Be}(\text{n}, \alpha){}^4\text{He}$  reaction is presently assumed to be negligible with respect to  ${}^7\text{Be}(\text{n}, \text{p}){}^7\text{Li}$ . However, depending on the results of ongoing experiments (these proceedings), it could reduce the lithium production by a few percents. The up to now overlooked  ${}^7\text{Be}(\text{n}, \text{p}\gamma){}^7\text{Li}$  channel could also have a similar effect [32].
- *The effect of electron screening or modification of decay lifetime is negligible.* For reactions of interest to BBN, screening affects the laboratory cross sections at too low energies [e.g.  $\lesssim 20$  keV

for  $D(d,p)^3H$  or  $^3He(d,p)^4He$ ] to affect measurement at BBN energies [ $\approx 100$  keV], on the one hand. On the other hand, the effect screening during BBN is completely negligible [33, 34]. It is well known that the lifetime of  $^7Be$  that decays by electron capture is modified in a plasma [35]. However, because of the Boltzmann suppression factor, at  $T < 0.5$  GK, the electron density is too low to provide the required reduction factor of  $\approx 3000$  on its 53 days half-life.

- Many exotic solutions to the lithium problem have been investigated (e.g. [36]), but most rely on extra neutron sources that *overproduce deuterium to levels now excluded by observations* [4, 19]. Few solutions beyond the Standard Model that do not suffer from this drawback are left, e.g. [37].
- *Stellar physics solutions requires a uniform reduction of surface lithium over a wide range of effective temperature and metallicity.* With some fine-tuning, this could be achieved by the combined effects of atomic diffusion and turbulence in the outer layers of these stars [38], or by lithium destruction, followed by a self-regulated re-enrichment of lithium by late time accretion [39].
- *There is no  $^6Li$  problem anymore.* A few years ago, observations [40] of  $^6Li$  in a few metal poor stars had suggested the presence of a plateau, at typically  $^6Li/H \approx 10^{-11}$ , orders of magnitude higher than the BBN predictions of  $^6Li/H \approx 1.3 \times 10^{-14}$  [41]. The uncertainties on the  $D(\alpha, \gamma)^6Li$  cross section have been experimentally constraint by a LUNA measurement [42] and by theory [43] confirming the BBN value. However, later, the observational  $^6Li$  plateau has been questioned due to line asymmetries which were neglected in previous abundance analyses. Hence, there is no remaining evidence for a plateau at very low metallicity [44] that can be used to derive a primordial  $^6Li$  abundance.
- With the high precision on D/H observations, the  $D(p, \gamma)^3He$ ,  $D(d, n)^3He$  and  $D(d, p)^3H$  rates need to be known at the percent level! This demands accurate measurement at BBN energies where data are scarce (see Fig. 2), to be compared with theories. The theoretical work of Arai *et al.* [21] was focused on low energies and does not correctly reproduce the  $D(d, n)^3He$  and  $D(d, p)^3H$  experimental data above  $\approx 600$  keV. It is highly desirable that these calculations be extended up to  $\approx 2$  MeV, to cover the range of experimental data and BBN energies.

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